Self-shunted Al/AlO$_x$/Al Josephson junctions

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Self-shunted aluminum Josephson junctions with high-transparency barriers were fabricated using the shadow-evaporation technique and measured at low temperatures, $T \approx 25\,\mathrm{mK}$. Due to high junction transparency, the IV-characteristics were found to be of only small hysteresis with retrapping-to-switching current ratio of up to 80 %. The observed critical currents were close to the Ambegaokar-Baratoff values (up to $80-100\,\%$). Good barrier quality was confirmed by the low subgap leakage currents in the quasiparticle branches, which makes the self-shunted Al junctions promising for application in integrated RSFQ-qubit circuitry.

Operation of superconducting electronic devices often implies an overdamped regime of Josephson dynamics [1]. An important example is given by a family of Rapid Single Flux Quantum (RSFQ) devices (see, e.g., a review Ref. [2]) traditionally based on resistively shunted junctions. A different type of shunting is however preferred, when using RSFQ-circuitry as control electronics for Josephson qubits [3]. For keeping low the overall decoherence, low-noise behaviour of the control RSFQ-circuit is required at qubit frequencies of the order of ten GHz (see, e.g., the analysis of decoherence of the flux qubit [4]). Due to large Niquist-Johnson fluctuations at low frequencies, this requirement can hardly be met with a standard low-ohmic linear shunting. Recently, several realizations of frequency-dependent damping for Josephson junctions have been proposed [5, 6, 7, 8]. In Refs. [5, 6], superconductor-insulator-normal metal (SIN) contacts were suggested as nonlinear shunts for Josephson junctions and their operation was analyzed in simple SFQ networks. A detailed study of subgap conductivity in highly-transparent SIN-junctions was presented in Ref. [7]. Another solution on the base of RC-shunting was considered by Hassel *et al.* [8], to be implemented in form of on-chip capacitors, added in series to the standard ohmic shunts.

In this Letter, we suggest an alternative approach on the basis of Al self-shunted Josephson junctions, making use of their highly nonlinear quasiparticle branches. The power spectrum $P_{\mathrm{Iqp}}(\omega)$ of current fluctuations of such a junction in the superconducting (S) state, $\langle V\rangle = 0$,

$$P_{\mathrm{Iqp}}(\omega) = (e/\pi) I_{\mathrm{qp}}(\hbar\omega/e) \coth(\hbar\omega/2k_{\mathrm{B}}T), \tag{1}$$

depends on the shape of its quasiparticle branch $I_{\mathrm{qp}}(V)$ [9] with the current suppressed at low temperatures, $k_{\mathrm{B}}T \ll \Delta$, in the subgap voltage range, $V \lesssim V_{\mathrm{g}} \equiv 2\Delta/e$. For Al junctions with the superconducting energy gap $\Delta \sim 200\,\mu\mathrm{eV}$, the gap frequency, $\omega_{\mathrm{g}} = 2\Delta/\hbar \sim 2\pi \times 10^{11}\,\mathrm{s}^{-1}$, far exceeds the typical qubit frequencies, thus enabling low decoherence on a time scale of qubit operation.

The fabrication routines for small Al/AlO$_x$/Al tunnel junctions are well developed, basing on the shadow evaporation technique [10]. In the early experiments, this technique has also been implemented for submicron self-shunted tunnel junctions composed of Pb-In/Pb [11]. Moreover, in the last years, it is widely applied for fabrication of Al-based qubits (see, e.g., the review on Josephson qubits in Ref. [12] and references therein). The latter fact enables, in principle, full on-chip integration of Al-RSFQ and Al-qubit circuitry, both operating in sub-Kelvin temperature range.

The intrinsic damping properties of an autonomous Josephson tunnel junction crucially depend on the barrier transparency, i.e., on the specific barrier resistance $\rho = R_{\mathrm{N}}A$, where R_{N} is the normal junction resistance and A is the junction area. Using for the critical current its Ambegaokar-Baratoff (AB) value at $T = 0$, $I_{\mathrm{c}} \approx I_{\mathrm{c}}^{\mathrm{AB}} = \pi\Delta/2eR_{\mathrm{N}}$, one can express the Stewart-McCumber damping parameter, $\beta_{\mathrm{c}} = 2eI_{\mathrm{c}}R_{\mathrm{N}}^2C/\hbar = \pi\Delta\rho c/\hbar$ as a function of ρ, Δ, and the specific junction capacitance $c = C/A$. The overdamping condition, $\beta_{\mathrm{c}} \lesssim 1$, thus imposes an upper boundary on the barrier transparency, $\rho \lesssim \hbar/(\pi\Delta c)$.

In experiment, non-hysteretic IV-curves [11, 13] and high-frequency operation of an RSFQ circuit [14] built on the self-shunted Nb/AlO$_x$/Nb junctions with ultrahigh-transparency barriers, $\rho \sim 1\,\Omega \times \mu\mathrm{m}^2$ (corresponding to the high critical current density $J_{\mathrm{c}} \sim 1-2\,\mathrm{mA}/\mu\mathrm{m}^2$), have been convincingly demonstrated. However the barrier quality was found to be not so high, due to noticeable density of pin-hole defects [13, 15] and, as a consequence, the considerable subgap leakage currents [13, 15, 16, 17].

An important advantage of Al-based over Nb-based junctions for the specific RSFQ-Qubit applications turns out to be a $7-8$ times smaller value of $\Delta \approx 180\,\mu\mathrm{eV}$ (corresponds to the zero-temperature BCS value $\Delta_0 = 1.76k_{\mathrm{B}}T_{\mathrm{c}}$ for $T_{\mathrm{c}} = 1.2\,\mathrm{K}$), which allows non-hysteretic behaviour of more opaque junctions with, typically, $\rho \lesssim 30\,\Omega \times \mu\mathrm{m}^2$. This decreases the risk of pin-hole defects and dramatically weakens the subharmonic gap structure of multiple Andreev reflection [15]. In the reported here experiments with Al junctions, we found the values of I_{c} to be slightly below their AB values. We also show that the nonlinearity parameter $\eta \equiv [G(0)R_{\mathrm{N}}]^{-1} \sim 10-30$, where $G(0)$ is the zero-bias conductance, substantially exceeds the values $\eta \sim 1$ measured in high-transparency

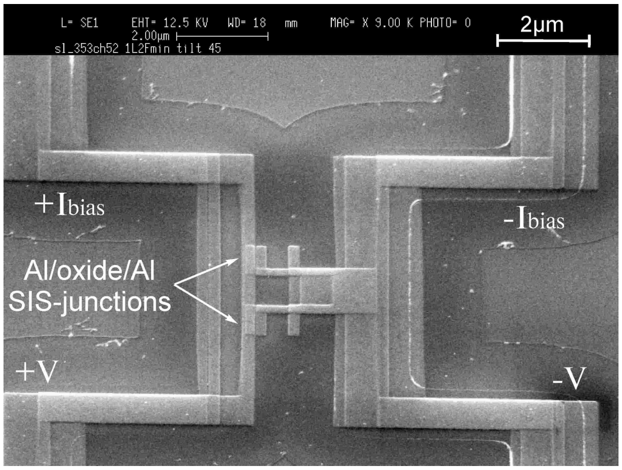

FIG. 1: SEM-micrograph of the two-junction SQUID. The junction is formed between the first and the third layers of Al, whereas the second layer (middle shadow of the mask) is not used in this structure. The IV-curves were measured using a four-point configuration.

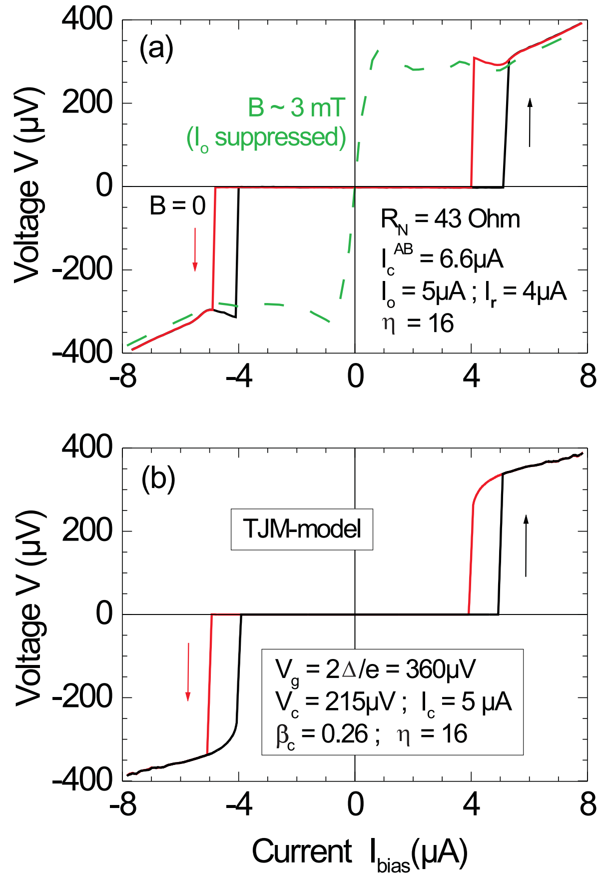

FIG. 2: (a) Typical current voltage characteristics of a two-junction Al-SQUID, demonstrating a small remaining hysteresis of the supercurrent. When the supercurrent is suppressed by magnetic field, $BS = \Phi_0(n+1/2)$, where $\Phi_0 = 2.07\times10^{-15}$ Wb is the flux quantum, nonlinearity of the quasiparticle branch with $\eta \approx 16$ is observed. (b) TJM-model simulation of an SIS-junction with the value of β_c giving the best agreement with experiment. The model does not take into account the junction overheating effects, which were observed in experiment in form of a local back-bending of IV-curves.

Nb-junctions [13, 15, 17].

In order to enable on-chip comparison between junctions with different parameters, the sample was designed to include three consecutive Al layers ("shadows"), 30, 40 and 20 nm thick. The layers were deposited *in situ* at three different angles, $-22°, +11°$ and $+22°$, respectively, through the same PMMA/Ge/Copolymer mask, $0.1/0.05/1.2\,\mu$m-thick, with suspended bridges. The first (the rightmost) shadow of Al was weakly oxidized at $P_{O_2} = 0.1$ Pa for 5 min to form a thin tunnel barrier. A set of junctions with two different transparencies was formed in overlaps between the first and either the second or, after prolonged oxidation of the first Al shadow by adsorbed oxygen, the third layer (cf. similar design for Al/Cu/Cu SIN-junctions in Ref. [7]). The results are reported for two- and four-junction SQUIDs with a total junction area $A \approx 2\times(0.25\times1)\,\mu\mathrm{m}^2$ and $A \approx 4\times(0.25\times0.5)\,\mu\mathrm{m}^2$, respectively; the SQUID loop area was $S \sim (1\times1)\,\mu\mathrm{m}^2$. A typical SQUID-device is shown in Fig. 1. We found an on-wafer spread of tunnel resistances of less than $10-20\,\%$, indicating good junction uniformity.

The IV-characteristics (see an example in Fig. 2(a)) were measured at $T \approx 25$ mK in the current-bias mode. The obtained values of the switching current, $I_o = 5.2\,\mu\mathrm{A}\pm10\,\%$ ($J_c \sim 10\,\mu\mathrm{A}/\mu\mathrm{m}^2$) and the retrapping current, $I_r = 3-4.4\,\mu$A, correspond to a small hysteresis of 20 to 40 % and to an appreciable pair-current suppression factor [18], $\alpha \equiv I_o/I_c^{AB} \sim 0.8$. To find $I_c^{AB} \approx 6.4\,\mu$A we used an asymptotic junction resistance, $R_N = 44\,\Omega\pm10\,\%$ (corresponding to a value of $\rho \approx 22\,\Omega\times\mu\mathrm{m}^2$). Using a typical values of the specific junction capacitance, $c \approx 50-75\,\mathrm{fF}/\mu\mathrm{m}^2$, we evaluate the McCumber parameter, $\beta_c \sim 0.8-1.2$. In the junctions with higher transparency (with $\rho = 10-12\,\Omega\times\mu\mathrm{m}^2$), formed between the first and the second shadows of Al, we found $I_o = 10-13\,\mu$A, $I_r = 7-9\,\mu$A, and $I_c^{AB} \approx 13\,\mu$A. Despite the smaller value of $\beta_c \sim 0.5$, a width of hysteresis was comparable to that of the lower-transparency junctions.

A width of hysteresis of ~ 20 % found in most of the junctions agrees roughly with the RSJN model using the values of $\beta_c \sim 0.5-1$ and an effective quasiparticle resistance at $V \lesssim V_c$, $R_J \sim (2-4)R_N$ (see, e.g., Fig. 4 in Ref. [19]). However, more accurate calculations in the frame of the tunnel junction microscopic (TJM) model (see, e.g., Ref. [1] and the references therein), accounting for the experimental value of α, produced the IV-curves, see Fig. 2(b), in agreement with experiment, but corresponding to a lower value of $\beta_c \approx 0.3$. The lower effective

value of β_c indicates a stronger damping in our experiment than the predicted intrinsic damping due to quasiparticle tunnelling only. An additional damping mechanism possibly arises due to a high-frequency shunting effect of the junction by the on-chip wiring impedance. This effect should be appreciable due to the relatively high values of R_N which are comparable to a typical microstrip-line impedance, $R_e \sim 10 - 100\,\Omega$ (see, e.g., [20]), and can explain a similar hysteresis in the junctions of different transparency. An opposite effect of wiring was a larger hysteresis, up to 44 %, in those junctions which had the shortest connecting paths, $\sim 100\,\mu$m long, to the wide leads of large capacitance. In practice, this contribution can be considerable in the systems of submicron tunnel junctions, but it can be reduced using, for instance, adjacent biasing resistors.

The measurably larger retrapping current values can also be an effect of thermal fluctuations, activated predominately in the resistive (R) state due to the junction self-heating. Using the model for noise-induced R→S transitions, Ref. [21], and the parameters of our junctions, we found a realistic estimate for the effective temperature in the R-state, $T^* \sim 1\,\mathrm{K} < T_c$. This estimate is consistent with the pronounced back-bending which is seen in the IV-curves in Fig. 2(a) (cf., e.g., Ref. [22]), and the observed $\sim 20\%$ reduction in the effective value of V_g at $I \gtrsim I_o$.

The quasiparticle branches of the IV-curves, like that shown by the dashed line in Fig. 2, were measured in the SQUIDs with a supercurrent suppressed by a magnetic field. The subgap conductance was found to be low, $[G(0)]^{-1} \sim 1\,\mathrm{k}\Omega$, which would allow low decoherence rates [4] in all-Al RSFQ-qubit circuits. High values were obtained for the nonlinearity parameter η, which were larger than both in the Nb-based junctions [13, 17] and in the Al SIN-junctions [7]. Similar to the case of SIN-junctions, the values of η were found to depend on the junction configuration and size. In particular, the largest value of $\eta \approx 32$, obtained in the four-junction SQUID, exceeded $\eta \approx 16$, measured in the two-junction SQUID with the two times larger junctions. In these two devices (not shown), the junctions were simply formed as overlaps of the straight perpendicular microstrips. A lower value of $\eta = 8.8$ was, however, found in a structure shown in Fig. 1 with one of electrodes made of "Γ"-shape (both right electrodes of the junctions; we call this configuration an "electron confinement shape"). The observed dependencies can be interpreted following the argument developed in Ref. [23] for describing an enhancement of the Andreev reflection processes due to coherent two-electron (quasiparticle) diffusion in the junction electrodes. (See for a more detailed discussion Ref. [7].)

To conclude, we investigated the damping in self-shunted Josephson junctions of type Al/$\mathrm{AlO_x}$/Al of high transparency, fabricated using a shadow-evaporation technique. The IV-characteristics were featured by a critical supercurrent of the order of 10 μA and a small hysteresis down to 20 %. Strong subgap nonlinearity of the quasiparticle branches was observed, which enables low decoherence in RSFQ-qubit integrated circuitry on the basis of Al junctions.

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